Liquefaction Susceptibility Mapping in Memphis/Shelby County, TN

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Investigations

Cone penetration test (CPT) data were collected in several geologic regions in the Memphis, Tennessee area. The liquefaction potential of each geologic region was calculated based on the simplified approach proposed by Youd et al. (2001). The approach compares the seismic demand given in terms of the cyclic stress ratio to the seismic capacity expressed as the cyclic resistance ratio. The liquefaction potential index (LPI) is calculated as a weighted average of the liquefaction susceptibility at each depth increment.

The liquefaction potential is based on several probabilistic parameters. The cyclic stress ratio (CSR) is a function of the peak horizontal acceleration at the ground surface, the total and effective vertical overburden stresses at a given depth, and a depth-dependent stress reduction coefficient. The stress reduction coefficient was assumed to be deterministic. The total and effective overburden stresses were calculated based on a constant mass density ($\rho = 1.6$ g/cm^3). The liquefaction potential was calculated for several peak ground acceleration values (0.1 g, 0.2 g, 0.3 g, 0.4 g) and a moment magnitude of 7.5.

The cyclic resistance ratio (CRR) is a function of the cone tip resistance (q_t) and sleeve resistance (f_s) measured in the field, and the total and effective overburden vertical stress. The total and effective stresses were calculated based on a constant mass density as previously discussed. The location of the groundwater table in the Memphis area was estimated from wells in the region. The statistics of q_t and f_s were calculated and used to generate simulated profiles for each geologic region. Finally, the liquefaction potential index (LPI) of each geologic region was calculated.

Results

Groundwater Table Map

The liquefaction potential of a site is dependent on the location of the groundwater table. Data from USGS groundwater monitoring wells were used to estimate the depth to the groundwater table. The data are available at the website http://waterdata.usgs.gov/nwis. More than 400 wells were used to generate a map of the mean depth to the top of the groundwater table. Figure 1 shows the contours to the groundwater table calculated using kriging. The contour map is shown with the geologic maps developed by the USGS Memphis Mapping Group.

Statistical Analysis of CPT Profiles

Twenty-nine CPT profiles were obtained from seven sites representing five different geologic regions in Memphis based on geologic maps developed by the USGS. Table 1 classifies the CPT profiles based on the location within the geologic regions identified by the USGS Memphis Mapping Group.

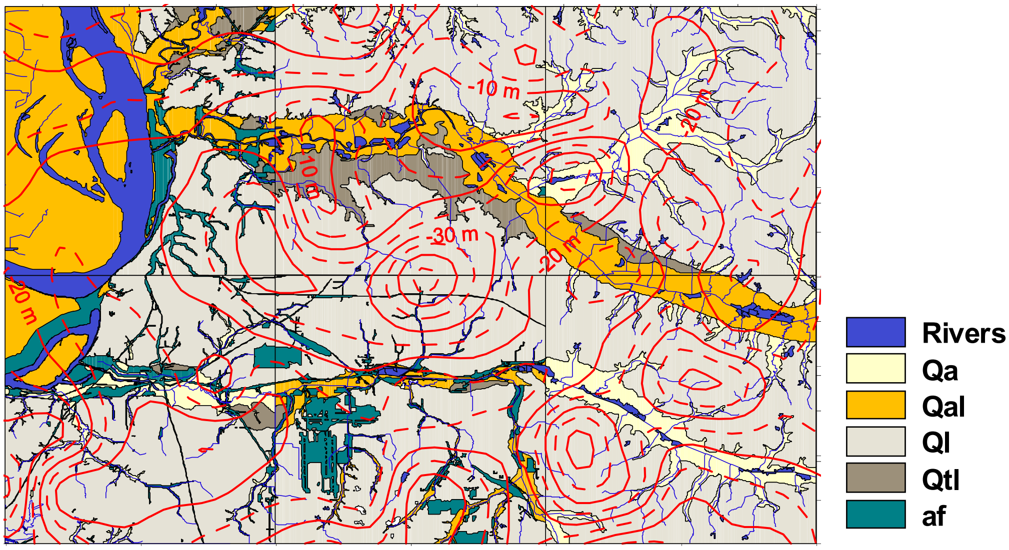


Figure 1 Contour map of depth to the groundwater table and geologic map of 6 quadrangles in the Memphis area.

Table 1 Location of CPT Profiles Based on Geology

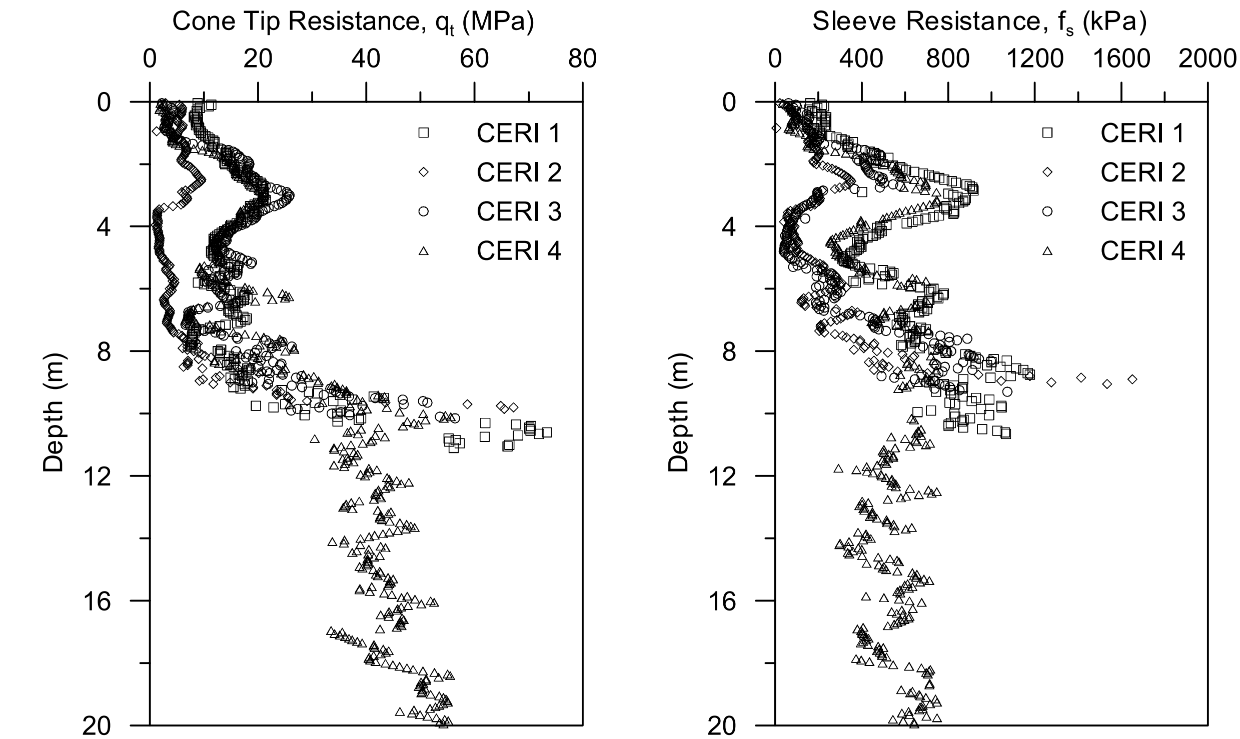
Geologic Region	Site	CPT Profile
Af	Mud Island	A11, A12, B, B1, C1, D1, E1
Qa		
Qal	Treatment Plant, Wolf River*, Shelby Farms	SWG 1, SWG 2 Wolf 1, Wolf 2, Wolf 3, Wolf 4, Wolf 5, Wolf 6, Wolf 7 Shoot A, Shoot B, Shoot C
Ql	CERI, Shelby Forest*	CERI 1, CERI 2, CERI 3, CERI 4 Forst 4, Forst 5, Forst 6, SFOR 1
Qtl	Trailer Park	TRPK 1, TRPK 2

* Site not in Memphis quadrangles

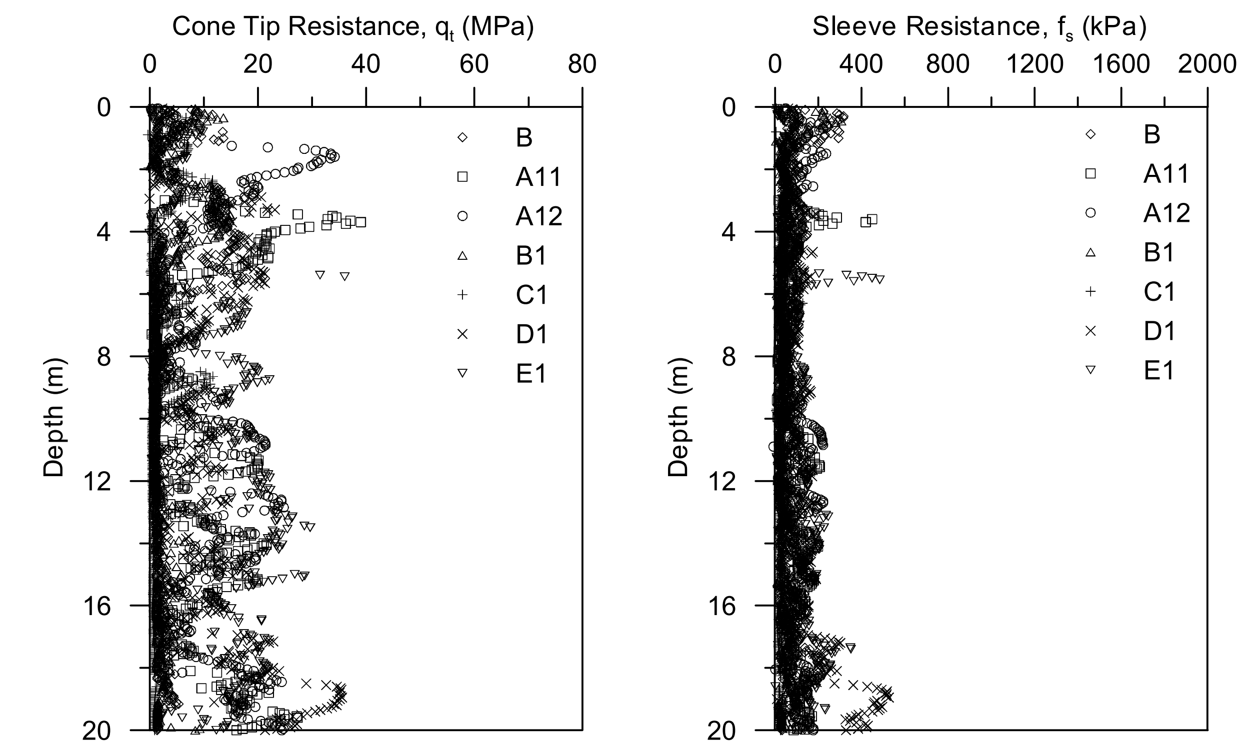
The two measurements of interest for liquefaction analysis are the cone tip resistance (q_t) and the sleeve resistance (f_s). Both of these measurements were recorded at 0.05-meter increments. Liquefaction is assumed to be constrained to the upper 20 meters. Therefore, only measurements recorded in the upper 20 meters were considered in the analyses. The q_t and f_s profiles are shown in Figure 2 for two sites in the Memphis area.

Simulation of CPT Profiles

Since only a limited number of CPT profiles were obtained for each geologic region, simulated profiles were generated to account for the uncertainty within each geologic region based on the lognormal mean and variance calculated for q_t and f_s. Two methods were evaluated for generating simulated profiles. The first approach assumed a lognormal distribution of the measured parameters for each depth. Simulated profiles are then generated based on the calculated mean and variance at each depth increment. This approach does not consider the correlation of q_t and f_s with depth or the correlation between q_t and f_s. The second approach uses the autocorrelation function to simulate CPT profiles and is discussed below.



(a) CERI site at the University of Memphis



(b) Mud Island

Figure 2 CPT profiles measured at (a) CERI at the University of Memphis and (b) Mud Island.

Autocorrelation Method

Each cone penetration tip resistance (q_t) profile was subdivided into separate layers by visually inspecting the q_t profile to identify depth intervals with similar characteristics. For each layer, the mean and standard deviation of $\log_{10}(q_t)$ were determined. The mean and standard deviation were used to calculate a standard normal residual value of q_t using the following expression:

$$q_{norm} = \frac{\log_{10}(q_t) - \mu_{\log_{10}(q_t)}}{\sigma_{\log_{10}(q_t)}}$$

where μ denotes the mean and σ denotes the standard deviation. An example is shown in Figure 3. The standard normal residual values of q_t are approximately normally distributed as shown in Figure 4.

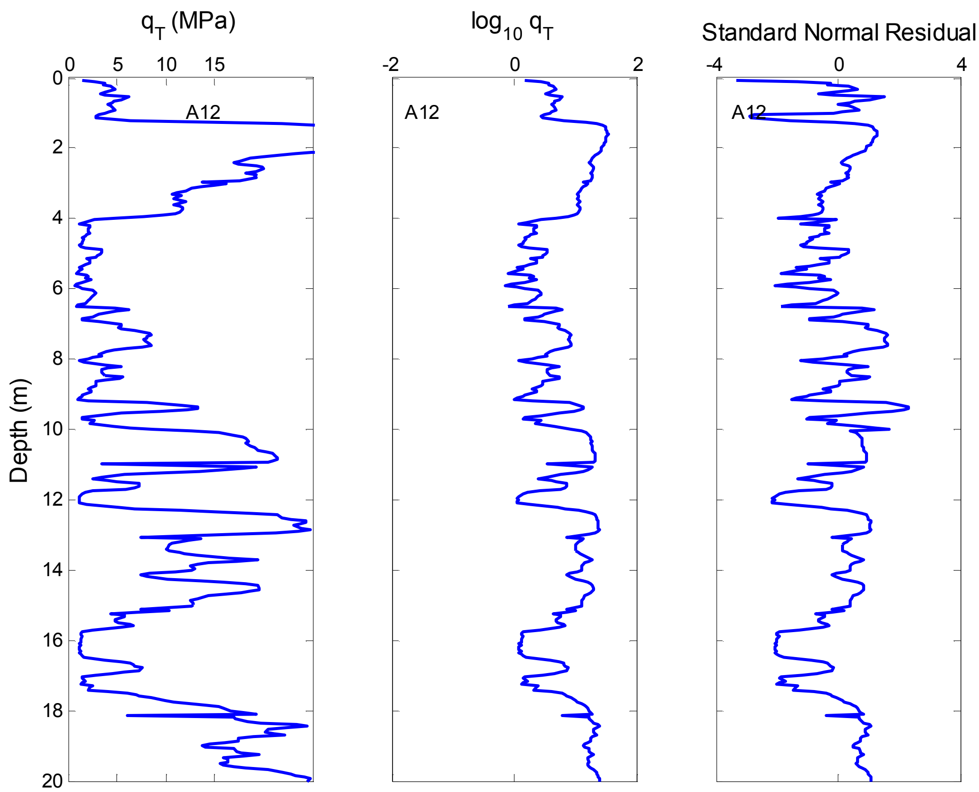


Figure 3 Example of (a) q_t, (b) $\log_{10}(q_t)$, and (c) standard normal residual q_t profiles for Mud Island Site A12.

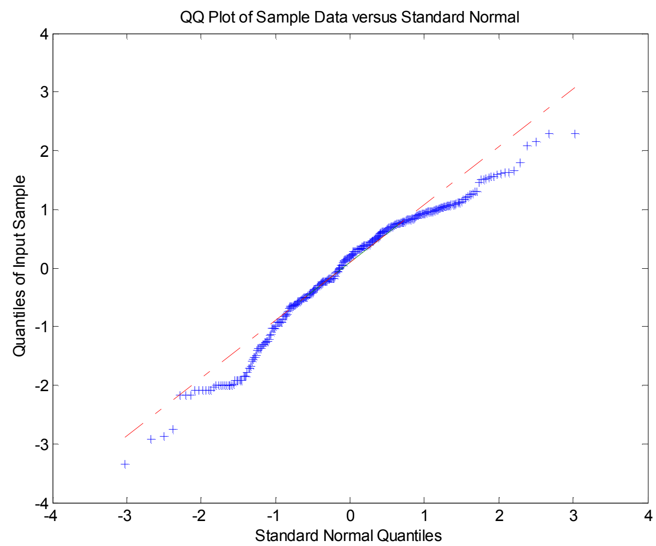


Figure 4 Quantile-quantile plot of standard normal residual q_t data

The autocorrelation function of the standard normal residual q_t profile was calculated to determine the spatial correlation of cone penetration data in the vertical direction. An example is shown in Figure 5. The experimental autocorrelation function was fitted using an exponential model described by:

$$\rho(h) = \exp\left(\frac{-3h}{a}\right)$$

where ρ is the correlation coefficient, h is the spatial lag, and a is the effective range (Deutsch and Journal, 1998). The effective range characterizes the spatial correlation of q_t.

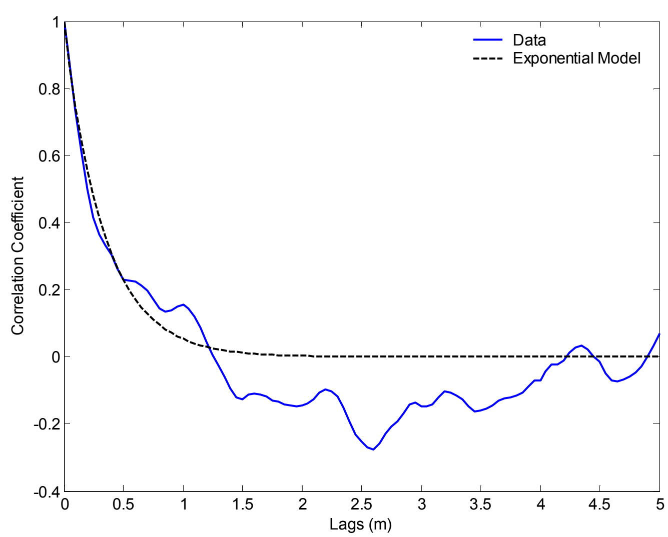


Figure 5 Experimental autocorrelation function and exponential model

Two hundred unconditional simulations of each q_t profile (defined by the mean and standard deviation of each layer and the effective range) were generated using the LU decomposition algorithm contained in

GSLIB, a geostatistical software library (Deutsch and Journel, 1998). Taken as whole, the 200 simulated profiles have the same statistical properties (mean, standard deviation, and autocorrelation structure) as the corresponding experimental q_t profile.

Evaluation of the liquefaction resistance using CPT data also requires profiles of the sleeve friction. As such, it was necessary to jointly simulate f_s profiles. This was achieved by calculating the probability density function (pdf) for f_s conditional on q_t as shown in Figure 6. For each value of q_t, the corresponding value of f_s was randomly selected using the probability density function.

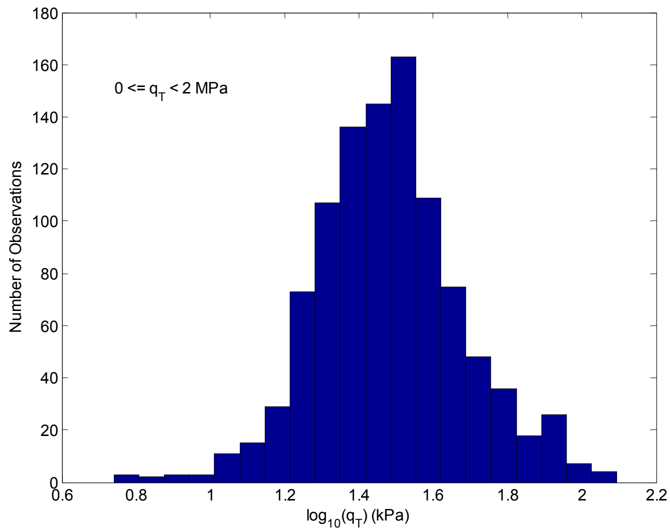


Figure 6 Probability density function for f_s conditional on q_t.

Figure 7 shows an example of the simulated profiles generated using each method described above. The autocorrelation method, which uses the autocorrelation structure as well as the mean and variance, produces CPT profiles that are more realistic than using only the mean and variance. Therefore, the autocorrelation method is used to simulate CPT profiles for assessing the liquefaction potential index.

Liquefaction Analysis

A total of 1200 simulated profiles were generated using each method described above. The simulated q_t and f_s profiles were then analyzed to determine the liquefaction potential index (LPI). Analyses were conducted for a moment magnitude (M_w) of 7.5 and a peak ground acceleration (a_{max}) values of 0.1 g, 0.2 g, 0.3 g, 0.4 g. Figure 8 shows the histogram and associated probability density function (pdf) of the computed LPI values for the 1200 simulations generated using the mean and variance for peak ground acceleration values of 0.1 g, 0.2 g, and 0.3 g. Figure 9 shows the histogram and pdf of the computed LPI values for the simulated profiles generated using the autocorrelation method. The autocorrelation method produces wider probability density functions due to the more realistic profiles generated.

Each measured CPT profile was analyzed to determine the liquefaction potential index (LPI). The results are shown in Figures 8 and 9. Most of the LPI for the measured profiles are located at the tails of the narrow probability density function produced by simulating profiles using only the mean and variance. In contrast, the LPI of the measured profiles is better described by the autocorrelation method.

The probability of exceeding a particular liquefaction potential index can be calculated from the probability density functions. Based on Iwasaki (1982), the liquefaction severity classifies the LPI to define the potential for liquefaction as shown in Table 2.

Table 2 Liquefaction Severity as a function of Liquefaction Potential Index

Liquefaction Severity	LPI
Little to none	LPI = 0
Minor	0 < LPI < 5
Moderate	5 < LPI < 15
Major	15 < LPI

The probability of exceeding an LPI of 15 for the simulated profiles based on the mean and variance is 0%, 82.5%, and 100% for a M_w of 7.5 and an a_{max} of 0.1 g, 0.2 g, and 0.3 g, respectively. For the simulated profiles generated by the autocorrelation method, the probability of exceeding an LPI of 15 is 0.006%, 80.4%, and 99.8% for the same M_w and a_{max} values. Therefore, the autocorrelation method is more conservative at low peak ground acceleration values and less conservative at higher a_{max} values due to the wider probability density function. However, the wider pdf is more representative of the CPT profiles obtained in the field.

Further Studies

The autocorrelation method for simulating CPT profiles will be used to model the uncertainty of liquefaction potential index in the geologic deposits found in the Memphis area. Probabilistic liquefaction potential maps will be developed for several peak ground acceleration values and moment magnitudes.

Non-Technical Summary:

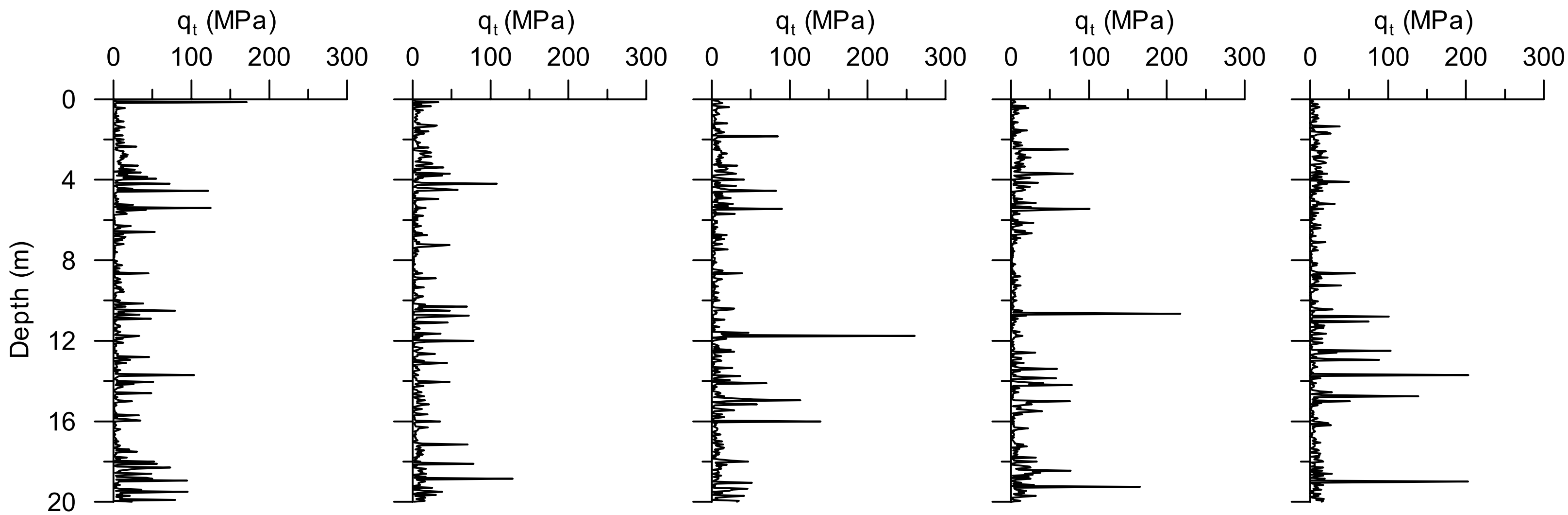
Simulated CPT profiles were generated using two approaches to represent the uncertainty in measuring field parameters. The autocorrelation method produces more realistic CPT profiles and the probability density function calculated from the results models the measures CPT profiles in the field. Using the methodology developed, a probability of exceeding a given liquefaction potential index can be calculated and used to estimate damage due to an earthquake.

Data Availability Statement

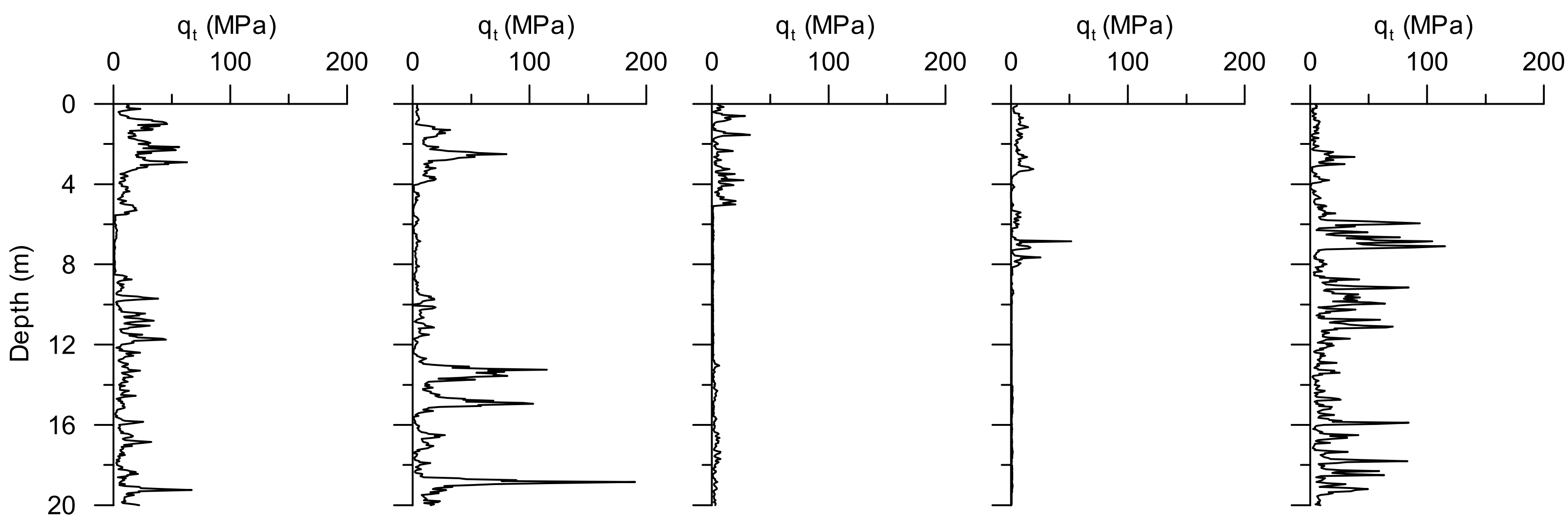
The CPT data compiled is available for distribution from the author. The groundwater table data is available at the website http://waterdata.usgs.gov/nwis.

Reference

Deutsch, C.V. and A.G. Journel, (1998). *GSLIB: Geostatistical Software Library and User's Guide*, 2nd Edition, Oxford University Press, New York.



(a) Profiles generated using mean and variance



(b) Profiles generated using autocorrelation method

Figure 7 Simulated random cone tip resistance (q_t) profiles using (a) the mean and variance at each depth (b) autocorrelation method of q_t at all depths.

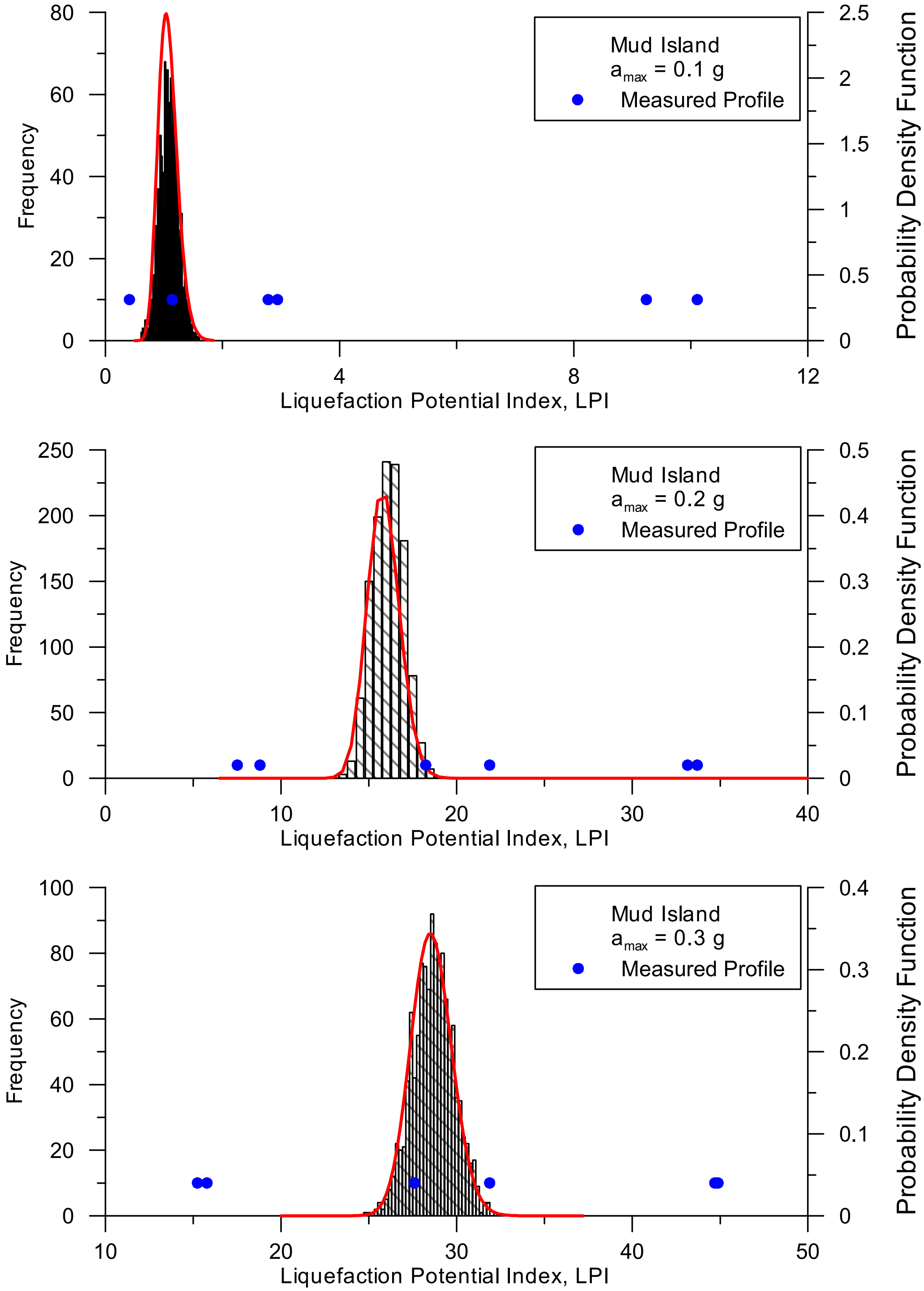


Figure 8 Histogram and corresponding probability density function of liquefaction potential index (LPI) for 1200 simulated profiles using mean and variance at each depth for a moment magnitude (M_w) of 7.5 and a peak horizontal ground acceleration (a_{max}) of (a) 0.1 g, (b) 0.2 g, and (c) 0.3 g.

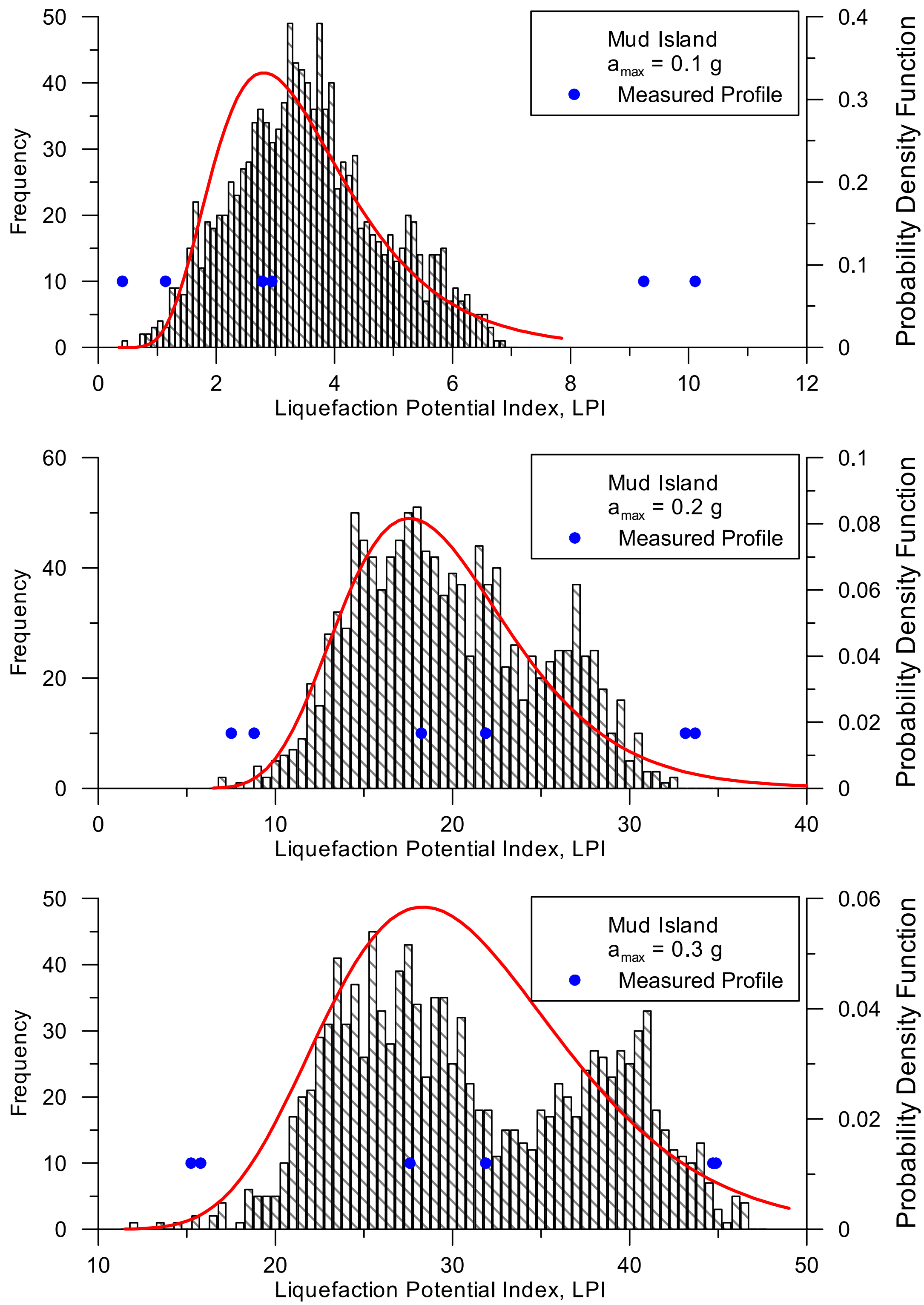


Figure 9 Histogram and corresponding probability density function of liquefaction potential index (LPI) for 1200 simulated profiles using autocorrelation method for a moment magnitude (M_w) of 7.5 and a peak horizontal ground acceleration (a_{max}) of (a) 0.1 g, (b) 0.2 g, and (c) 0.3 g.